78-12-131 WRD RESOURCE ROOM

WH15

Owen K. Williams

An Evaluation of Problems Arising from Acid Mine Drainage in the Vicinity of Shasta Lake Shasta County California

U. S. GEOLOGICAL SURVEY

Water-Resources Investigations 78-32

Prepared in cooperation with the
CALIFORNIA REGIONAL WATER QUALITY
CONTROL BOARD - CENTRAL VALLEY REGION

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

BIBLIOGRAPHIC DATA SHEET

1. Report No.

2.

3. Recipient's Accession No.

4. Title and Subtitle

AN EVALUATION OF PROBLEMS ARISING FROM ACID MINE DRAINAGE IN THE VICINITY OF SHASTA LAKE, SHASTA COUNTY, CALIFORNIA

5. Report Date May 1978

6.

7. Author(s) Fuller, Richard H., Shay,. Johnevan M., Ferreira, Rodger F., and Hoffman, Ray J.

8. Performing Organization Rept. No. USGS/WRI-78-32

9. Performing Organization Name and Address

U.S. Geological Survey, Water Resources Division
345 Middlefield Road
Menlo Park, Calif. 94025

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Address

U.S. Geological Survey, Water Resources Division
345 Middlefield Road
Menlo Park, Calif. 94025

13. Type of Report & Period Covered Final

14.

15. Supplementary Notes

Prepared in cooperation with the California Regional Water Quality Control Board--Central Valley Region

16. Abstracts

Streams draining the mined areas of massive sulfide ore deposits in the East and West Shasta Mining Districts of northern California are generally acid and contain large concentrations of dissolved metals, including iron, copper, and zinc. The streams, including Flat, Little Backbone, Spring, West Squaw, Horse, and Town Creeks, discharge into Shasta Lake and the Sacramento River and have caused numerous fish kills. The major source of pollution is discharge from underground mines. A secondary source of pollution is streamflow and surface runoff that has passed through mine dumps where the oxidation of pyrite and other sulfide minerals results in the production of acid and the mobilization of metals.

Suggested methods of treatment include the use of air and hydraulic sealing of the mines, lime neutralization of mine effluent, channeling of runoff and mine effluent away from mine and tailing areas, and the grading and sealing of mine dumps. A comprehensive preabatement and postabatement monitoring program is recommended in order to evaluate the effects of any treatment method used.

17. Key Words and Document Analysis. 17a. Descriptors

*Acid mine water, *Copper, *Iron, *Zinc, *Mine drainage, California, Pyrite, Water pollution sources

17b. Identifiers/Open-Ended Terms

East Shasta Mining District, Shasta County, West Shasta Mining District

17c. COSATI Field/Group

18. Availability Statement

No restriction on distribution.

19. Security Class (This Report) UNCLASSIFIED

20. Security Class (This Page UNCLASSIFIED

21. No. of Pages 44

22. Price

AN EVALUATION OF PROBLEMS ARISING FROM ACID MINE DRAINAGE IN THE VICINITY OF SHASTA LAKE, SHASTA COUNTY, CALIFORNIA

By Richard H. Fuller, Johnevan M. Shay, Rodger F. Ferreira,
and Ray J. Hoffman

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 78-32

Prepared in cooperation with the
California Regional Water Quality Control Board
Central Valley Region

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

6206-09

May 1978

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

H. William Menard, Director

For additional information write to:

District Chief
Water Resources Division
U.S. Geological Survey
345 Middlefield Rd.
Menlo Park, Calif. 94025

CONTENTS

Page

Conversion factors---------- IV

Abstract---------- 1

Introduction---------- 2

Purpose and scope---------- 2

Study area---------- 3

Mining history---------- 6

Field studies of streams---------- 6

Acid generation and dissolved metals in four basins---------- 12

West Squaw Creek drainage basin---------- 12

Keystone Mine---------- 12

Balaklala Mine---------- 13

Shasta King Mine---------- 13

Little Backbone Creek drainage basin---------- 17

Mammoth Mine---------- 17

Golinsky Mine---------- 17

Other drainage basins---------- 18

Flat Creek drainage basin---------- 18

Spring Creek drainage basin---------- 18

Acid generation and metal mobilization---------- 19

General processes---------- 19

Processes in mine waste piles---------- 21

Biological indicators---------- 22

West Squaw Creek---------- 26

Little Backbone Creek---------- 26

Laboratory studies---------- 27

Control of acid mine effluent---------- 29

Sealing mines---------- 30

Treatment of effluent---------- 31

Runoff and infiltration control---------- 31

Conclusions and recommendations---------- 31

Suggested abatement procedures---------- 32

Water-monitoring program---------- 37

References cited---------- 38

ILLUSTRATIONS

Page

Figure 1. Index map showing chemical-quality sampling sites, November 1974 and April 1975 samplings---------- 4

2. Map showing benthic sampling sites, and analyses of sampling on West Squaw Creek---------- 16

3. Map showing benthic sampling sites, and analyses of sampling on Little Backbone Creek---------- 23

Page
Figure 4. Graph showing pH of oxygenated water and deoxygnated water flowing through columns of Balaklala Mine dump material-- 28
5. Schematic diagram of proposed acid mine-drainage abatement procedures for the Weil Portal area------------------------ 35

TABLES

Page
Table 1. Selected water characteristics, November 1974 sampling-------- 7
2. Selected water characteristics, April 1975 sampling----------- 8
3. Instantaneous metal loads for the November 1974 sampling------ 10
4. Instantaneous metal loads for April 1975 sampling------------- 11
5. Analyses of acid effluent and streams receiving effluent------ 14
6. Benthic sample analyses, West Squaw Creek drainage------------ 24
7. Benthic sample analyses, Little Backbone Creek drainage------- 25

CONVERSION FACTORS

For readers who may prefer to use metric units (International System or SI units) rather than English units, the conversion factors for the terms used in this report are listed below:

English	*Multiply by:*	*Metric (SI)*
ft (feet)	3.048×10^{-1}	m (meters)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic meters per second)
in (inches)	2.54×10^{1}	mm (millimeters)
in^2 (square inches)	6.452×10^{-4}	m^2 (square meters)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)

Degrees Fahrenheit are converted to degrees Celsius by using the formula:

$$°C = \frac{5}{9}(°F-32).$$

Abbreviations used in text:
kg/d - kilograms per day
mg/L - milligrams per liter
µg/L - micrograms per liter
µmho/cm - micromhos per centimeter

AN EVALUATION OF PROBLEMS ARISING FROM ACID MINE DRAINAGE IN THE VICINITY OF SHASTA LAKE, SHASTA COUNTY, CALIFORNIA

By Richard H. Fuller, Johnevan M. Shay,
Rodger F. Ferreria, and Ray J. Hoffman

ABSTRACT

Streams draining the mined areas of massive sulfide ore deposits in the East and West Shasta Mining Districts of northern California are generally acid and contain large concentrations of dissolved metals, including iron, copper, and zinc. The streams, including Flat, Little Backbone, Spring, West Squaw, Horse, and Town Creeks, discharge into Shasta Lake and the Sacramento River and have caused numerous fish kills. The major source of pollution is discharge from underground mines. A secondary source of pollution is streamflow and surface runoff that has passed through mine dumps where the oxidation of pyrite and other sulfide minerals results in the production of acid and the mobilization of metals.

Suggested methods of treatment include the use of air and hydraulic sealing of the mines, lime neutralization of mine effluent, channeling of runoff and mine effluent away from mine and tailing areas, and the grading and sealing of mine dumps. A comprehensive preabatement and postabatement monitoring program is recommended in order to evaluate the effects of any treatment method used.

INTRODUCTION

The East and West Shasta Mining Districts of northern California have produced over 50 percent of the copper mined in California (Kinkel and others, 1956). The mining operations, beginning in the 1860's and continuing until 1963, resulted in local degradation of water quality. Surface water that drains part of these areas is noted for its poor chemical quality, having a low pH and high concentrations of dissolved metals, including iron, copper, and zinc. In that region, streams affected by degraded water are readily identifiable because their streambeds are stained with iron precipitates.

In recent years, much concern has been expressed over the poor quality of the water discharged from the Shasta Mining Districts into Shasta Lake, Keswick Reservoir, and the Sacramento River. Discharge of water of poor quality has resulted in numerous fish kills (Hansen and Weidlein, 1974), as well as the addition of toxic metals to the Sacramento River.

Purpose and Scope

The U.S. Geological Survey, in cooperation with the California Regional Water Quality Control Board--Central Valley Region, undertook this investigation in 1974 to determine the extent of water-quality degradation and possible methods of reducing acid-water discharge from the Shasta Mining Districts.

The scope of the study included the following areas of effort:

1. Determine the extent and magnitude of acid and metal pollution, including the delineation of possible point sources of effluent.
2. Choose a limited number of areas for more comprehensive studies of the specific causes of acid water and associated metal concentrations. These studies included both laboratory and field investigations.
3. Suggest possible methods to minimize or treat mine effluent in order to neutralize the pH and reduce the discharge of dissolved metals, and design a demonstration project for water-quality control in a selected element of the drainage system.
4. Design a water-quality monitoring program that could be used to evaluate the effectiveness of treatment or abatement methods that may be used in the future.

The assistance is greatly appreciated of the staff of the California Regional Water Quality Control Board--Central Valley Region, the California Department of Fish and Game, Paul Lindberg and Earl Schuman of the Anaconda Company, and Ronald D. Hill, Director, Resources Extraction and Handling Division of the U.S. Environmental Protection Agency in Cincinnati.

Study Area

The East and West Shasta Mining Districts are in the Klamath Mountains of Shasta County in northern California (fig. 1). The East Shasta District has an area of about 90 mi^2 and the West Shasta, about 200 mi^2. The districts are in rugged country typified by steep V-shaped valleys. The lower slopes of the districts are covered by chaparral, including large quantities of manzanita (*Arctostaphylos* sp.). A number of species of oak and some pines and firs are also common. The upper slopes of the districts, originally forested with conifers, were cut to provide timber for the mines. Fires and acid fumes from smelters also helped denude many of the slopes. Today these areas are developing good stands of second-growth timber. Species common to the upper slopes include sugar pine (*Pinus lambertiana*) and ponderosa pine (*P. ponderosa*) with chaparral inhibiting second growth on some slopes (Albers and Robertson, 1961; Kinkel and others, 1956).

The climate of the area is typified by hot summers and moderate winters. Summer daytime temperatures are often 100°F to 105°F and occasionally exceed 110°F. The mean July temperature is 81°F. In January, the coldest month of the year, the mean temperature is 42°F, with a record low mean for January of 22°F (Albers and Robertson, 1961). Mean annual precipitation is about 61 inches.

The geology of the East Shasta District was discussed in detail by Albers and Robertson (1961) and that of the West Shasta District by Kinkel and others (1956), and the geology of both districts was summarized by Nordstrom and others (1977). The following information on geology is taken from those reports.

Formations in the area range in age from Early Devonian to Triassic and are composed of interbedded sedimentary and volcanic rocks. The stratigraphic section has a thickness of up to 20,000 ft. Intrusive igneous bodies of Late Jurassic or Early Cretaceous age occur within the section. Much of this area is complexly deformed by folding and faulting.

Mineralization is generally found in three types of deposits; these are "massive sulfide replacement deposits, contact metasomatic magnetite deposits and gold-bearing quartz veins" (Albers and Robertson, 1961). Massive sulfide bodies are found in the Balaklala Rhyolite, localized along shear zones in the Bully Hill Rhyolite, and along faulted contacts between the Bully Hill and Pit Formation. Mineralization was attributed to ascending hydrothermal fluids. The source of metal that was mined in the East Shasta District is probably volcanic and sedimentary rocks underlying both the Bully Hill Rhyolite and the Pit Formation and from an igneous mass of which the Pit River stock may be a cupola.

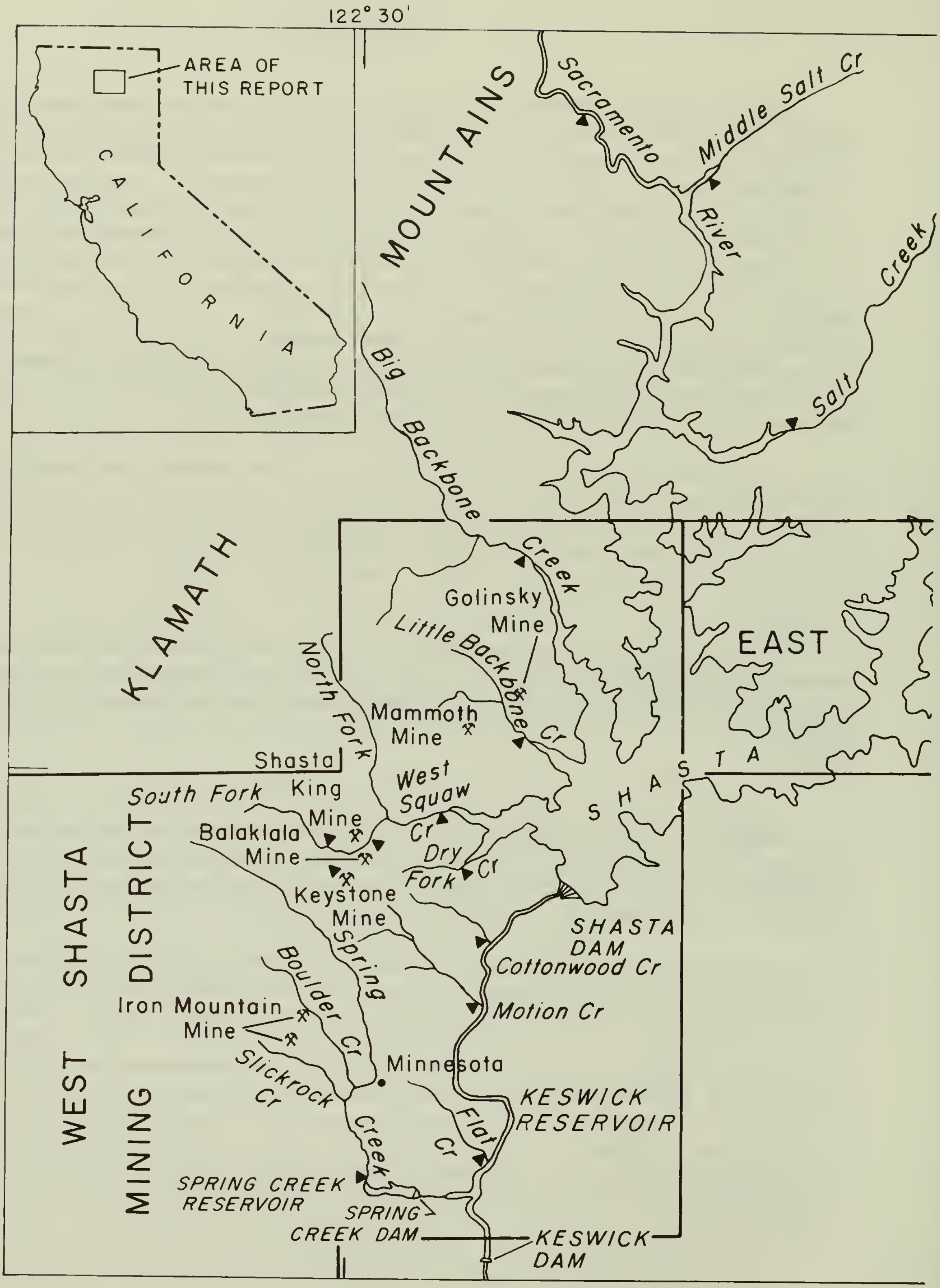
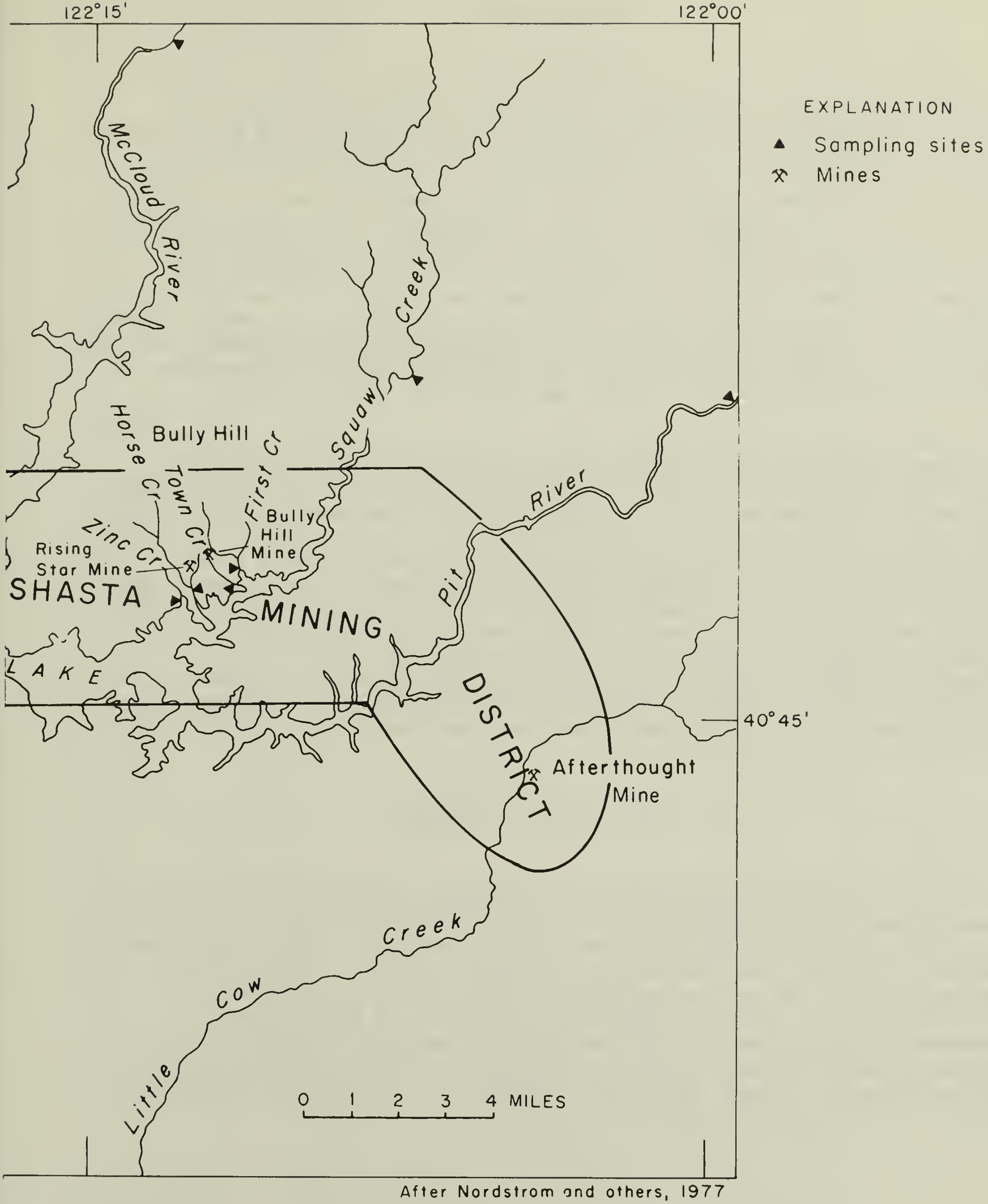


FIGURE 1.--Index map showing chemical-quality



After Nordstrom and others, 1977

sampling sites, November 1974 and April 1975 samplings.

Mining History

Mining activity in the East Shasta District began in 1853 with the discovery of placer gold deposits in Town Creek just east of Bully Hill. Metallic copper and silver were also found in the placers. From 1862 through 1899, most of the mining in the district was limited to gold and silver in gossan (oxidized ores) overlying sulfide bodies. Between 1900 and 1920, copper mining reached its peak, with gold and silver recovered as byproducts. Zinc-rich ore was also mined at the Bully Hill Mine. Little mining was done between 1921 and 1927 owing to litigation brought against smelter owners because smoke and fumes were killing vegetation in the vicinity of the smelters. Following 1927, little mining was done because of low metal prices. Between 1942 and 1944, magnetite was produced at the Shasta Iron Mine. Some exploration was done at the Bully Hill and Afterthought Mines between 1942 and 1955 but no production was recorded. No appreciable mining has been done in the area since the mid-1950's (Albers and Robertson, 1961).

Early exploration of the West Shasta District was for gold deposits. Gossan outcrops in the Iron Mountain area were found to have appreciable quantities of silver with some gold, and in 1879, a silver extraction plant was constructed. Between 1879 and 1895, silver ore was mined at Iron Mountain from gossan. Copper mining was begun in 1897 in the Iron Mountain area. In addition, pyrite for sulfuric acid production was mined in later years. Copper production in the West Shasta District reached its peak between 1898 and 1919. Some zinc was recovered from the Iron Mountain and Mammoth Mines. The Iron Mountain Mine was operated until 1962; in the last years of operation, mining was restricted to pyrite for use in sulfuric acid production. Since 1962, there has been some exploration in the district, but no mining activity. A plant to recover copper from mine effluent at Iron Mountain presently is maintained by the Stauffer Chemical Corporation.

FIELD STUDIES OF STREAMS

The initial phase of the study was designed to determine the acid and dissolved-metal concentrations in all tributaries with a drainage area greater than 8 mi^2 that enter Shasta Lake and Keswick Reservoir so that significant sources of acid and dissolved metals could be documented. This initial sampling was done during two sampling periods, one in early November 1974, a period of low flow, and one in April 1975, a period of higher flow. A comprehensive discussion of the November 1974 sampling and analytical techniques was presented by Nordstrom and others (1977). Sampling sites for the two periods are shown in figure 1. Data from November 1974 are shown in table 1, and those from April 1975 are in table 2.

TABLE 1.--*Selected water characteristics, November 1974 sampling*

[From Nordstrom and others, 1977]

Station	Sampling date (1974)	Dis-charge (ft^3/s)	Specific conduc-tance (µmho/cm)	pH	Dis-solved iron (µg/L)	Dis-solved manganese (µg/L)	Dis-solved cadmium (µg/L)	Dis-solved copper (µg/L)	Dis-solved zinc (µg/L)
Dry Fork Creek	11-8	0.49	59	7.35	6	1.7	0.05	0.08	--
West Squaw Creek	11-5	3.66	225	3.82	3,500	430	11	2,000	3,800
Little Backbone Creek	11-5	1.19	532	3.15	11,700	280	60	3,900	9,500
Big Backbone Creek	11-5	10.8	78	7.15	69	26.8	.2	.6	4.24
Sacramento River	11-5	298	149	8.4	20	5.6	<.05	.6	.40
Middle Salt Creek	11-5	3.21	138	7.70	21	11.6	<.05	.3	.62
Salt Creek	11-5	2.94	153	7.38	65	46	<.05	.7	1.44
McCloud River	11-5	336	108	8.10	16	4.6	<.05	.9	.18
Zinc Creek at Squaw Creek	11-6	.01	136	6.69	43	20.8	<.05	1.0	.92
Horse Creek at Squaw Creek	11-6	.43	350	5.63	90	260	45	1,310	7,000
Horse Creek, Right Fork above falls	11-6	--	2,550	2.85	30,000	2,030	340	9,200	50,000
Horse Creek, Right Fork below falls	11-6	--	2,520	2.85	30,000	2,030	340	9,200	50,000
Horse Creek, Right Fork	11-6	--	2,520	2.85	30,000	2,100	340	9,200	52,000
Horse Creek, Left Fork	11-6	--	152	7.42	180	17.2	.05	20	50
First Creek at Squaw Creek	11-6	.13	112	6.96	7	1.7	<.05	1.2	.54
Town Creek (no flow)	11-6	--	--	--	--	--	--	--	--
Squaw Creek	11-6	21.3	235	7.00	8	12	<.05	1.0	.46
Pit River below dam	11-6	3,710	138	7.85	8	1.9	<.05	.5	.22
Cottonwood Creek	11-7	4.22	72	7.2	11	12.8	.20	3.2	3.08
Motion Creek	11-7	5.83	65	7.1	8	22	<.05	3.7	.42
Flat Creek	11-7	1.64	295	4.85	125,000	550	80	600	980
Spring Creek	11-8	4.91	1,620	2.95	125,000	1,420	200	4,300	8,000

TABLE 2.--*Selected water characteristics, April 1975 sampling*

[From Nordstrom, written communication, 1976]

Station	Sampling date (1975)	Discharge (ft^3/s)	Specific conductance (µmho/cm)	pH	Dissolved iron (µg/L)	Dissolved manganese (µg/L)	Dissolved cadmium (µg/L)	Dissolved copper (µg/L)	Dissolved zinc (µg/L)
Dry Fork Creek	4-10	9.72	33	6.5	8.5	1.8	0.03	0.7	2.1
West Squaw Creek	4-10	123	103	4.02	650	50	4.7	650	630
West Squaw Creek, Balaklala Mine effluent at main adit, 2,480-ft altitude	4-10	2.36	675	3.23	29,000	660	40	6,250	7,000
West Squaw Creek below Weil Portal	4-10	3.33	1,250	3.8	127,000	600	80	16,500	14,500
West Squaw Creek 100 ft above Shasta King Mine	4-10	37.2	379	3.59	13,450	120	14	2,450	2,100
Little Backbone Creek	4-10	31.2	260	3.61	6,000	60	14	1,400	1,900
Big Backbone Creek	4-10	305	45	6.5	12	.6	.07	.4	2.1
Sacramento River	4-02	2,280	81	7.78	12	1.6	.02	.3	.40
Salt Creek	4-02	107	72	6.95	7.0	1.4	.02	.2	.13
McCloud River	4-02	1,250	100	6.8	4.0	.7	.01	.2	.13
Zinc Creek	4-02	.41	57	6.70	7.0	.2	.03	.2	.73
Horse Creek at confluence	4-02	--	128	6.4	165	52	16	370	370
Horse Creek, Right Fork	4-02	.52	1,470	3.3	49,000	750	240	8,900	32,200
Horse Creek, Left Fork	4-02	2.18	65	7.70	5.0	7.0	.32	.5	16
First Creek	4-02	5.32	52	7.30	5.0	.2	.05	1.6	1.4
Town Creek	4-02	1.84	298	4.70	85	300	130	4,500	12,000
Pit River below dam	4-03	8,370	113	--	8.5	2.5	.04	4.5	.7
Little Cow Creek	4-03	788	84	--	8.0	6.0	.27	6.4	58
Cottonwood Creek	4-03	5.44	52	6.2	7.0	.6	.05	.7	2.2
Motion Creek	4-03	15.8	58	6.1	--	11.5	.14	4.0	23
Flat Creek	4-03	6.85	106	7.12	11.5	57	14	4.6	150
Spring Creek	4-03	75.4	1,390	2.72	108,000	430	80	1,780	1,120

In order to determine the relation of the metal load of each stream studied to the total load of dissolved metals being added to the reservoirs, metal loads were computed from metal concentrations and discharge measurements. Table 3 shows the metal loads for the November 1974 sampling and table 4 for the April 1975 sampling. These load computations were made using instantaneous flow measurements with a single sample taken for dissolved metals. Computation of load is based on the assumption of a constant flow and constant dissolved-metal concentration during a day. It should be noted that the toxic effects of acid and dissolved metals are a function of concentration and not of load.

Data shown in tables 1 and 2 indicate that six creeks in the study area have very high concentrations of dissolved metals. These are Flat Creek, Little Backbone Creek, Spring Creek, and West Squaw Creek in the West Shasta District; Horse Creek and Town Creek in the East Shasta District. During the two sampling periods, these streams carried dissolved-metal loads which account for most of the metals being discharged into the upper Sacramento River system. In terms of total load, the six creeks carried 95.2 to 98.6 percent of the dissolved iron, 47.0 to 57.6 percent of the dissolved manganese, 92.8 to 99.6 percent of the dissolved cadmium, 86.0 to 93.7 percent of the dissolved copper, and 83.1 to 98.5 percent of the dissolved zinc. Spring Creek is the largest contributor of dissolved metals, followed in order of decreasing contribution by West Squaw Creek, Little Backbone Creek, Town Creek, Horse Creek, and Flat Creek. In terms of copper and zinc, which may have the greatest toxicity in the system, 49.9 percent of the total dissolved-copper load is from Spring Creek, followed by 22.6 percent from West Squaw and 13.3 percent from Little Backbone Creeks. Spring Creek accounts for 41.5 percent of the dissolved zinc followed by West Squaw Creek with 22.3 percent, and Little Backbone Creek with 17.5 percent of the total dissolved zinc. Some of the dissolved-metal loads for the upper Sacramento, Pit, and McCloud Rivers, as well as for Little Cow Creek, are large because of the volume of water rather than the high concentrations of dissolved metals.

After delineating the six creeks that transport acid effluent and large concentrations of dissolved metals, the examination of sources, extent, and causes of pollution was undertaken in the West Squaw Creek and Little Backbone Creek drainage basins of the West Shasta District. These basins were chosen because of their large contribution of acid and metals and because they are more accessible than some of the other drainage basins. Spring Creek, the major carrier of degraded water in the area, was given only a cursory evaluation in this study because it was being studied in detail by D. K. Nordstrom as part of his Ph.D. dissertation at Stanford University. Flat Creek, the other acid and metal carrier in the West Shasta District, was also given a cursory evaluation because, although it had high concentrations of dissolved metals, its loads were relatively small compared to other streams in the study area. The streams of the East Shasta District which carry acid mine effluent are Horse Creek and Town Creek flowing from the Bully Hill mining complex, and Little Cow Creek from the Afterthought Mine area. These streams were not studied beyond the initial determination of their acid and metal concentrations. Information on causes of acid-effluent generation and methods for the treatment or abatement of acid water gained in the study of the West Shasta District should be transferable to the problems of the East Shasta District.

TABLE 3.--*Instantaneous metal loads for the November 1974 sampling*

[From Nordstrom and others, 1977]

Location	Iron		Manganese		Cadmium		Copper		Lead		Zinc	
	kg/d	Percent[1]	kg/d	Percent[1]	kg/d	Percent[1]	kg/d	Percent[1]	kg/d	Percent[1]	kg/d	Percent[1]
Dry Fork Creek	0.007	0	0.002	0	--	--	0.0009	0	--	--	--	--
West Squaw Creek	31.3	1.4	3.8	7.3	0.1	3.2	17.9	19.8	0.02	4.5	34.0	19.8
Little Backbone Creek	34.1	1.6	.8	1.6	.2	6.5	11.4	12.6	.05	11.4	27.7	16.1
Big Backbone Creek	1.8	.1	.7	1.4	.005	.2	.02	0	--	--	.1	0
Sacramento River	14.6	.7	4.1	8.0	--	--	.4	.4	.3	68.2	.3	.2
Middle Salt Creek	.2	0	.09	.2	--	--	.002	0	.003	.7	.005	0
Salt Creek	.5	0	.3	.6	--	--	.005	0	.002	.5	.01	0
McCloud River	13.1	.6	3.8	7.3	--	--	.7	.8	--	--	.2	.1
Zinc Creek	.0007	0	.0004	0	--	--	.00002	0	--	--	.00002	0
Horse Creek	.09	0	.3	.6	.05	1.6	1.4	1.5	.0005	.1	7.4	4.3
First Creek	.002	0	.006	0	--	--	.0004	0	--	--	.0002	0
Town Creek (no flow)												
Squaw Creek	.4	0	.6	1.2	--	--	.05	0	--	--	.02	0
Pit River	72.8	3.3	17.3	33.6	--	--	4.5	5.0	--	--	2.0	1.2
Cottonwood Creek	.1	0	.1	.2	.002	.1	.03	0	.03	6.8	.03	0
Motion Creek	.1	0	.3	.6	--	--	.05	0	--	--	.006	0
Flat Creek	501	23.1	2.2	4.3	.32	10.4	2.4	2.7	.003	.7	3.9	2.3
Spring Creek	1,500	69.1	17.1	33.2	2.4	77.9	51.6	57.1	.03	6.8	96.1	56.0
Total load	2,170		51.5		3.1		90.5		.44		171.8	

[1] Percentage of total load for the metal designated.

TABLE 4.--*Instantaneous metal loads for the April 1975 sampling*

[Calculated from discharge and concentrations given by Nordstrom, written communication, 1976]

Location	Sampling date (1975)	Iron		Manganese		Cadmium		Copper		Zinc	
		kg/d	Percent[1]	kg/d	Percent[1]	kg/d	Percent[1]	kg/d	Percent[1]	kg/d	Percent[1]
Dry Fork Creek	4-10	0.20	0	0.042	0	0.0007	0	0.02	0	0.049	0
West Squaw Creek	4-10	196	1.0	15	8.5	1.4	7.0	196	25.4	190	24.7
Little Backbone Creek	4-10	46	.2	4.6	2.6	1.1	5.5	107	13.9	145	18.9
Big Backbone Creek	4-10	9.0	0	.4	.2	.05	.2	.29	0	1.6	.2
Sacramento River	4-2	67	.3	8.9	5.0	.11	.5	1.8	.2	2.2	.3
Salt Creek	4-2	1.8	0	.036	0	.005	0	.05	0	.034	0
McCloud River	4-2	12	0	2	1.1	.03	.1	.6	0	.39	0
Zinc Creek	4-2	.007	0	.002	0	.00003	0	.0002	0	.0007	0
Horse Creek, right fork	4-2	63	.3	.96	.5	.3	1.5	11	1.4	41	5.3
Horse Creek, left fork	4-2	.03	0	.04	0	.0017	0	.002	0	.09	0
First Creek	4-2	.07	0	.002	0	.0006	0	.02	0	.02	0
Town Creek	4-2	.38	0	1.4	.8	.56	2.8	20	2.6	54	7.0
Pit River below dam	4-3	174	.8	51	28.8	.82	4.1	92	12.0	14	1.8
Little Cow Creek	4-3	15	0	12	6.8	.52	2.6	12	1.6	110	14.3
Cottonwood Creek	4-3	.09	0	.007	0	.0006	0	.009	0	.03	0
Motion Creek	4-3	--	--	.44	.2	.005	0	.15	0	.89	.1
Flat Creek	4-3	.19	0	.96	.5	.23	1.1	.08	0	2.5	.3
Spring Creek	4-3	19,900	97.1	79	44.7	15	74.9	328	42.7	207	26.9
Total load		20,484		176		20		769		768	

---

[1] Percentage of total load for the metal designated.

ACID GENERATION AND DISSOLVED METALS IN FOUR BASINS

In order to evaluate the specific causes of acid water and high concentrations of dissolved metals, and the effects of this type of effluent on the aquatic ecosystem, an intensive study was made of the West Squaw Creek and Little Backbone Creek drainage basins. This study included an evaluation of acid generation and metal mobilization, additional sampling to determine specific sources of acid and dissolved metals, and an evaluation of the effects of specific sources of effluent on the chemical and biological quality of water in the two basins.

Most of the mining in the East and West Shasta Districts, after the initial precious-metal mining in the late 1800's, was for copper and later for pyrite, with secondary recovery of zinc and other metals. With the exception of the Iron Mountain Mine in the West Shasta District, where pyritic material was mined from an open pit, nearly all mining for copper in both districts was done underground. The ore deposits generally are massive pyrite (FeS_2) bodies with localized pods of chalcopyrite ($CuFeS_2$). Mining of chalcopyrite required the removal of large quantities of pyrite to reach the chalcopyrite pods. Pyrite removed from the mines was dumped on the steeply sloping hillsides and in the stream channels below the mine portals.

West Squaw Creek Drainage Basin

Keystone Mine

Maps of the Keystone Mine (Kinkel and others, 1956) indicate that there are three tunnels exiting the inner mine workings at altitudes of 3,136 ft, 3,106 ft, and 2,976 ft.[1] Only the 2,976-ft tunnel was observed in this study. Water flowing from this tunnel travels over tailings to a small area, excavated in the top of the dump, where it is ponded. This allows some of the iron to precipitate as ferric hydroxide before the water flows out of the pond. Some ferric sulfate precipitates also were noted around the edges of the pond.

Chemical analyses of water flowing from the Keystone Mine, and of the water in the pond, indicate that the water is acid (pH 3.5) as it flows from the mine; concentrations of dissolved metals are listed in table 5. The only significant change in the chemistry of the water as it is ponded is a loss of about half of the dissolved iron. Water flowing out of the pond forms a small stream that eventually flows into a caved stope of the Balaklala Mine.

---

[1] Altitudes of portals are given to facilitate locating portals on the maps of Kinkel and others (1956) and Albers and Robertson (1961).

The only plant life observed in the effluent water from the mine is some bacterial and filamentous algal growth that is generally covered with a thick coat of ferric hydroxide. The only animal life found in the mine effluent or the pond was a few water striders, *Gerris remigis*, and backswimmers, *Notonecta kirbyi*, on the surface of the pond.

Balaklala Mine

The Balaklala Mine is the largest mining complex in the West Squaw Creek basin. The main mine adit is at an altitude of 2,480 ft with a second adit, tunnel 11, at an altitude of 2,434 ft about 600 ft from the main adit. Effluent from both adits flows onto two dumps; the lower one of the two contains a shallow pond in which are found thick bacterial-algal matts covered with ferric hydroxide. Chemical analysis of water flowing from the two adits and from the pond indicates that the water is acid and contains rather large quantities of dissolved metals (table 5).

The Weil Portal of the Balaklala Mine (fig. 2) is the exit for a long tunnel which drains the lower workings of the mine. An estimated 50 percent of the massive dump outside the portal has been washed down the mountain into West Squaw Creek by a stream that flows through the dump. Effluent from the Weil Portal is the most acidic and has the highest dissolved-metal concentration of any water sampled during this study (table 5). The pH values are as low as 2.0 with correspondingly large dissolved-metal concentrations. The effluent, after flowing from the portal, mixes with water in a small unpolluted stream before flowing through the dump.

In addition to the aforementioned mine openings, maps of underground workings (Kinkel and others, 1956) indicate at least two other openings to the mine workings at an altitude of 2,482 ft. Many exploration tunnels, most of which are dry, are also found in the area.

Shasta King Mine

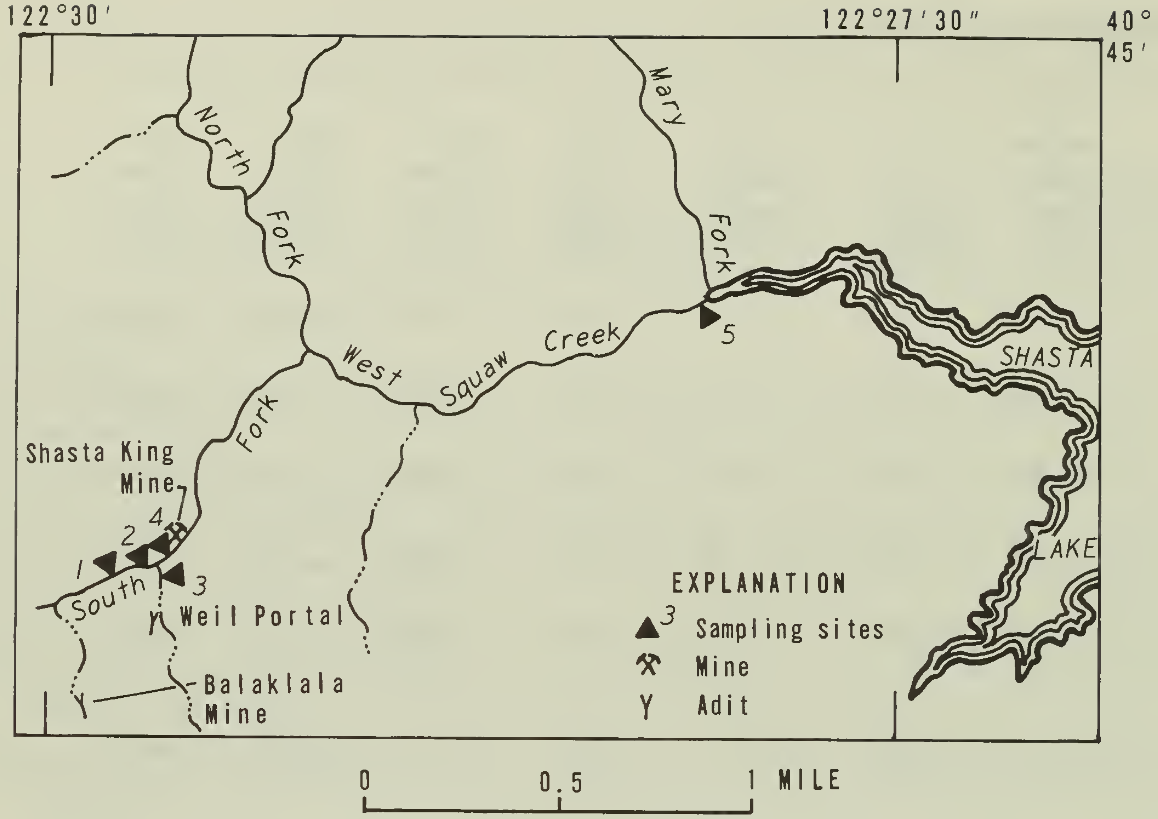
The Shasta King Mine is north of the South Fork of West Squaw Creek directly across from Weil Portal of the Balaklala Mine. The mine has eight adits, all facing West Squaw Creek and within a few hundred feet of the creek bottom. Dumps from the adits generally extend from the portals to the creek bottom so that much of the creek in front of the mine area now flows through coarse debris that originated as dump material. Much of this material is pyritic.

TABLE 5.--*Analyses of acid effluent*

Station	Date of collection	Discharge (ft^3/s)	Acidity as $CaCO_3$ (mg/L)	Specific conductance (µmho/cm)	pH
Keystone Mine effluent at main adit	9-17-75	0.08	68	340	3.5
Keystone Mine ponded effluent from main adit	9-17-75	--	60	370	3.4
Balaklala Mine effluent at main adit--2,480 ft altitude	9-17-75	.14	97	513	3.6
Balaklala Mine effluent from tunnel 11--2,434 ft altitude	9-17-75	.10	31	1,060	3.0
Balaklala Mine ponded effluent on dump draining tunnel 11--2,434 ft altitude	9-17-75	--	134	918	2.9
Balaklala Mine effluent at Weil Tunnel--2,249 ft altitude	9-17-75	.08	6,160	7,700	2.0
South Fork, West Squaw Creek just downstream from Shasta King Mine	9-18-75	5.0	65	277	4.6
Weil Tunnel effluent just before it enters West Squaw Creek	9-18-75	.25	3,160	3,550	2.6
West Squaw Creek at highway bridge just above Shasta Lake	9-18-75	6.0	164	607	3.0
Mammoth Mine effluent, Friday-Louden Tunnel, 870 ft level--2,426 ft altitude	9-18-75	.30	10	337	5.3
Mammoth Mine effluent, 470 ft level--2,820 ft altitude	9-18-75	.64	579	1,600	2.8
Mammoth Mine ponded effluent on bench at 2,820 ft altitude	9-18-75	--	574	1,640	2.8
Little Backbone Creek just above Shasta Lake	9-18-75	3.0	178	817	3.0

and streams receiving effluent

Dissolved iron (μg/L)	Dis-solved manganese (μg/L)	Sulfate (mg/L)	Dis-solved cadmium (μg/L)	Dis-solved cobalt (μg/L)	Dis-solved copper (μg/L)	Dis-solved lead (μg/L)	Dis-solved zinc (μg/L)
5,100	200	120	50	4	3,800	21	8,200
2,300	200	120	40	4	3,700	19	8,000
48,000	2,300	430	100	9	9,500	96	16,000
--	1,500	190	40	13	3,300	32	6,200
1,800	1,900	200	50	17	4,200	38	8,000
800,000	5,200	5,700	900	230	170,000	300	180,000
2,100	600	130	30	5	2,100	13	3,400
610,000	290	3,000	490	130	90,000	200	85,000
15,000	60	180	30	6	5,100	11	5,600
360	10	130	20	5	420	2	5,100
110,000	40	660	180	6	15,000	60	31,000
110,000	40	630	180	7	15,000	62	30,000
7,600	60	260	60	13	4,700	20	11,000



	Sampling site				
	1	2	3	4	5
Diversity	1.635	0.918	0.863	0.985	1.000
Number of species	6	2	2	2	2
Number of individuals per square meter	123.8	32.2	376.7	75.3	21.5
pH	3.6	3.5	2.1	2.75	2.9

FIGURE 2.--Benthic sampling sites, and analyses of sampling on West Squaw Creek.

Little effluent was flowing from any of the adits of the Shasta King Mine during field observations in the summer and autumn of 1975. Some water within the mine, however, had pH ranging between 2.0 and 2.5 and specific conductance of more than 7,500 µmho/cm. During winter and spring, some of this acid water may enter West Squaw Creek.

Little Backbone Creek Drainage Basin

Mammoth Mine

The Mammoth Mine, located on steeply sloping hills on the south side of Little Backbone Creek, has the largest complex of underground workings in the West Shasta District. The most striking feature of this mine complex is the large waste dumps that spill out from the various adits, forming terraces atop large piles of rubble on hillsides. The upper levels of the mine, above 2,980 ft altitude, seem to be dry with large collapsed areas being common (Kinkel and others, 1956). Lower areas of the mine contain adits from which highly acid water flows, containing high concentrations of dissolved metals. Water flowing from adits at an altitude of 2,820 ft is pooled on top of a large terraced dump before it flows over and through the dump into Little Backbone Creek. Chemical analyses of water flowing from the mine and from the pond indicate that the water is acid and contains large quantities of dissolved metals (table 5).

The lowest and longest tunnel of the Mammoth Mine is the Friday-Louden Tunnel. This tunnel exits the mine at an altitude of 2,426 ft into Shoemaker Gulch, nearly 3,000 ft south of the mine's main portals. Water from the tunnel had a pH of 5.3 and much lower concentrations of dissolved iron and copper than any other water sampled in the mine (table 5). This may be because of dilution of effluent with ground water of better quality. The main mine workings may be separated from the Friday-Louden Tunnel by caving.

Golinsky Mine

The Golinsky Mine is a small mine on the north side of Little Backbone Creek nearly opposite the Mammoth Mine. The main adits of the mine are at a lower altitude, 1,840 ft, than those of the Mammoth Mine. No effluent was observed at the mine in the summer and autumn of 1975; however, a number of small dry streambeds on the slopes below the mine were stained with iron oxide and with some iron sulfate and copper sulfate precipitates. The stains indicate that there is some flow or seepage from the mine, possibly in winter and spring.

Other Drainage Basins

Flat Creek Drainage Basin

Flat Creek drains an area north of the Spring Creek drainage basin. There are no major mines in this basin but at Minnesota, near the headwaters of the creek, a flotation plant was built to concentrate metals from ore taken from the Iron Mountain Mine. Crushed, processed waste ore forms a large dump through which water leaches, polluting the creek. Dump material is held back from the creek by a small dam, causing water to pond on the dump. This ponded water, percolating through the dump, yields additional acid and metals to Flat Creek.

Spring Creek Drainage Basin

The Spring Creek drainage basin was studied (Nordstrom and others, 1977; Nordstrom, 1977) concurrently with the work leading to this report, and is therefore given only a cursory evaluation here. The principal mine in this drainage basin is the Iron Mountain Mine, the largest mine in the area. Mining was open pit and underground, but during the last few years of operation (until 1962) it was entirely from an open pit. Spring Creek is the major single carrier of acid and metals to the upper Sacramento River (tables 3 and 4). Water from the creek is held behind the Spring Creek Debris Dam and discharged according to the flow of the Sacramento River so that the effluent will be diluted by river water and thus cause no major water-quality problem in the river. Periodic fish kills, however, continue to occur below Spring Creek according to reports by local residents.

Spring Creek has two major tributaries, Slickrock Creek and Boulder Creek. Slickrock Creek is the main carrier of acid and metals into Spring Creek (Nordstrom, 1977). Water quality is good in Spring Creek above its confluence with Boulder Creek.

Additional effluent to the system is wastewater from a copper concentrating plant at Iron Mountain. This plant extracts copper by replacing it with iron in acid water flowing from underground workings of the Iron Mountain Mine.

ACID GENERATION AND METAL MOBILIZATION

General Processes

The oxidation of pyrite and the subsequent oxidation of the ferrous iron released are the sources of acid. Stumm and Morgan (1970) proposed the following stoichiometric reactions for the oxidation of pyrite by oxygen in the presence of water.

$$FeS_2 + 7/2\ O_2 + H_2O \rightleftharpoons Fe^{+2} + 2SO_4^{-2} + 2H^+ \qquad (1)$$

$$Fe^{+2} + \tfrac{1}{4}O_2 + H^+ \rightleftharpoons Fe^{+3} + \tfrac{1}{2}H_2O \qquad (2)$$

$$Fe^{+3} + 3H_2O \rightleftharpoons Fe(OH)_3 + 3H^+ \qquad (3)$$

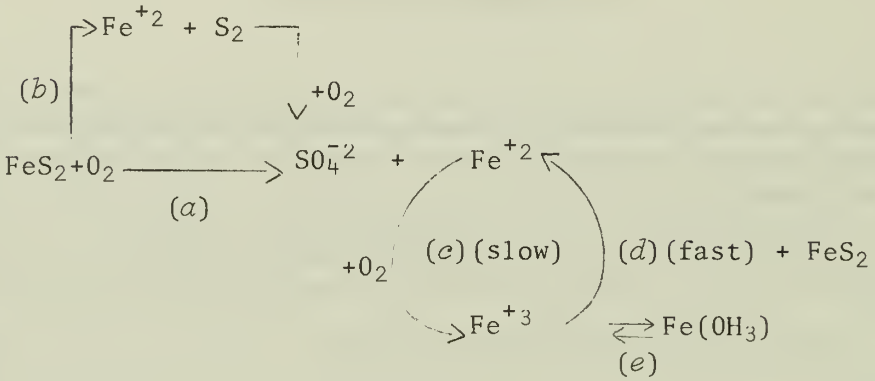
and the oxidation of pyrite by ferric iron,

$$FeS_2 + 14Fe^{+3} + 8H_2O \rightleftharpoons 15Fe^{+2} + 2SO_4^{-2} + 16H^+ \qquad (4)$$

As indicated in equation 1, the sulfide of the pyrite (FeS_2), in the presence of oxygen and water, is oxidized to sulfate with the release of ferrous iron, Fe^{+2}, and acid, H^+, into the system. The ferrous iron is then oxidized to ferric iron, Fe^{+3}, in the presence of oxygen and acid (equation 2). Ferric iron then hydrolyzes to form ferric hydroxide, $Fe(OH)_3$, with the release of additional acid (equation 3). Pyrite can also be oxidized directly by ferric iron (equation 4), forming ferrous iron and sulfate. It should be noted that much more acidity is produced by the oxidation of one mole of pyrite by ferric iron than with oxygen. The ferrous iron may then be reoxidized as shown in equation 2.

Because production of acid from pyrite generally starts with equation 1, it is evident that acid production is reduced when one of the constituents in the first half of the equation is removed or exhausted from the system, that is, the removal of pyrite, dissolved oxygen, or water from the system. If, however, the oxygen source is removed from a system, it is possible that acid will continue to be generated, via equations 3 and 4, with the ferric iron acting as the oxidizing agent. This reaction would continue until all ferric iron is converted to ferrous iron.

Stumm and Morgan (1970) proposed the following schematic model of the mechanisms for acid production for oxygenated water within a mine.



The process may be initiated with the oxidation of pyrite (*a*), or dissolution followed by oxidation (*b*). Ferrous iron is then very slowly oxidized by oxygen (*c*); this is the rate-determining step for the entire reaction. The resultant ferric iron is then rapidly reduced by the pyrite (*d*) to ferrous iron, and under oxygenated conditions the reaction is perpetuated. Precipitated ferric hydroxide (*e*) acts as a reservoir for ferric iron should the ferric ions in solution become depleted. Stumm and Morgan (1970) emphasized that micro-organisms, specifically autotrophic iron bacteria *Thiobacillus* and *Ferrobacillus ferrooxidans* may influence the rate of pyrite oxidation by mediating ferrous iron oxidation.

It should be noted that oxidation reactions like those which take place with pyrite, releasing iron into solution and generating acid, also take place with other sulfide minerals such as chalcopyrite ($CuFeS_2$), sphalerite (ZnS), galena (PbS), and greenockite (CdS), to name a few, releasing dissolved metals and acid. In addition, large amounts of metals may be brought into solution simply by acid dissolution of metallic sulfides at low pH (R. W. Potter, oral commun., 1976). An example of this type of reaction is shown in the dissolution of sphalerite, equation 5.

$$ZnS + 2H^{+} \leftrightarrows Zn^{+2} + H_2S\uparrow \qquad (5)$$

Dissolution of sulfide may well be the major method for the mobilization of metals, other than iron, in mines.

Processes in Mine Waste Piles

Two principal sources of acid generation and metal mobilization occur in the Shasta Mining Districts. The first and major source is pyritic ore, remaining in the mines, which comes in contact with oxygenated or ferric iron-bearing water moving through the mines. The second source is pyritic material in waste dumps of mine tailings outside the mines. In order to better understand the local processes of acid generation in mine-dump material and the contributions of effluent generated in dump material, supplementary field observations and laboratory studies were made. A study of sulfide ore weathering within the dumps (Potter, 1976) identified three types of mine dumps: (1) Waste piles composed primarily of processed ore, (2) waste piles predominantly of pyritic mine waste, and (3) piles primarily of country rock with little pyritic material present.

A large processed-ore waste pile from the Iron Mountain Mine is found at Minnesota (fig. 1), near the headwaters of Flat Creek, where crushed ore was piled following processing through a flotation plant. According to Potter (1976), the dump is composed predominantly of pyrite with minor amounts of quartz and can be divided into upper unsaturated and lower saturated zones. In the unsaturated zone of the dump, moderate quantities of sulfates were accumulating and, in certain areas, were cementing the upper zone. In the saturated zone, secondary copper sulfide minerals occurred as coatings on pyrite grains. This represents a zone of copper enrichment in which a secondary sulfide "ore body" is forming in the saturated zone. Water samples collected from the pond atop the Minnesota tailings dump and from a seep at the contact of the dump with an underlying older dump show metal enrichment as water flows through the upper dump. Although water increases in pH from 2.2 to 2.4 as it passes through the dump, it is enriched in iron by a factor of 5.0, in manganese by 7.8, in sulfate by 3.0, in cadmium by 1.2, in copper by 1.3, in silver by 4.0, and in zinc by 6.5 (Potter, 1976). This effluent is the source of pollution in Flat Creek.

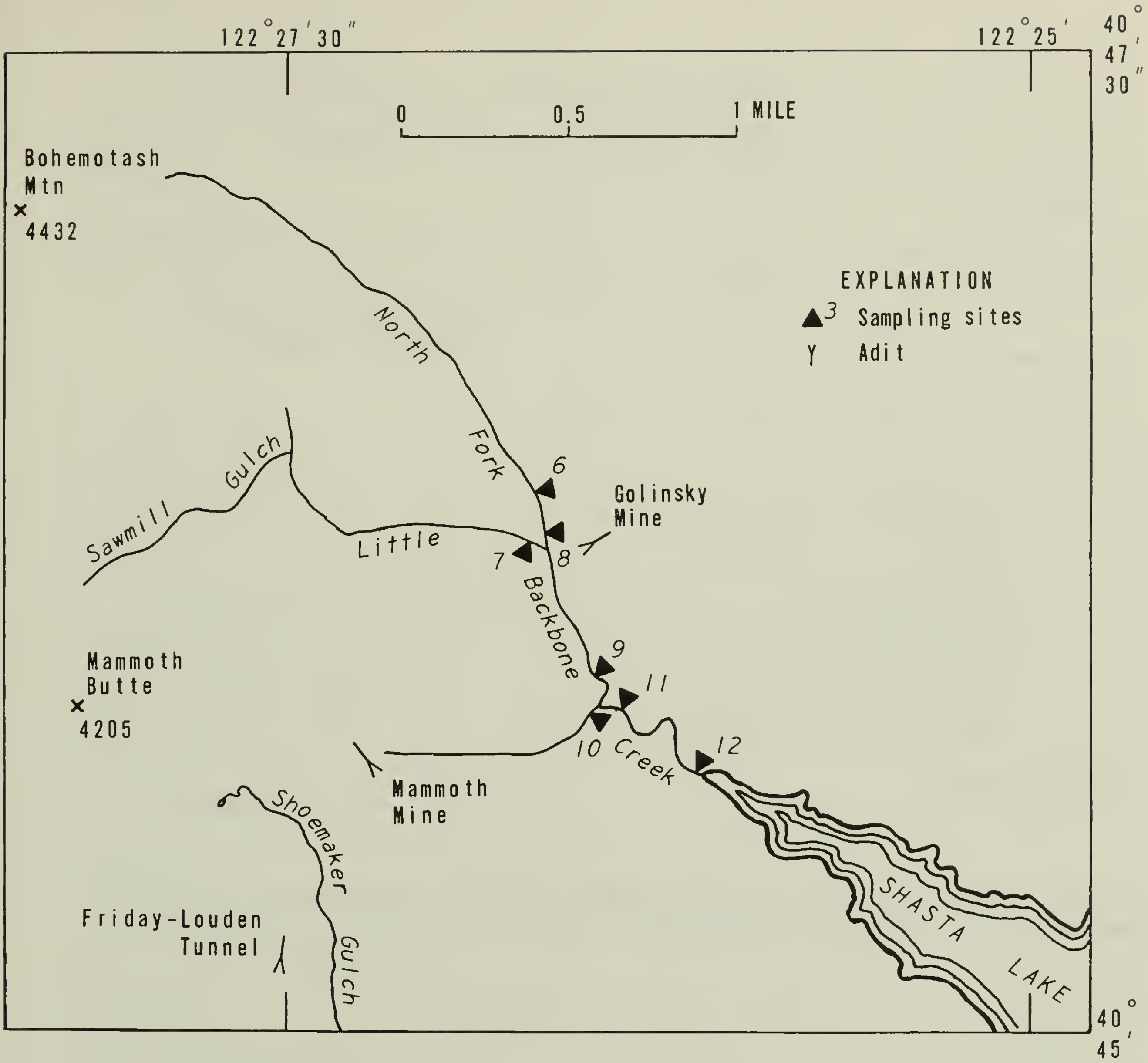
The second type of mine dump described by Potter is represented by the dump at the Keystone Mine. It is directly in front of the main portal and contains large amounts of sulfide minerals and only moderate amounts of country rock. The major sulfide mineral is pyrite with small amounts of chalcopyrite, sphalerite, tennantite-tetrahedrite, and galena. Grain size ranges from boulder to fine sand with the average size being between pebble and coarse sand. No secondary copper sulfide minerals were found in the dump; however, rhyolite underlying the dump has been intensively altered by Keystone mine effluent. Potter found that organic material within the dump is enriched in mobile elements in the reducing environments that surround the organics. Deposits of ferric sulfate around the edges of the ponded area on the mine dump and on exposed pyritic material add to the dissolved constituent load of West Squaw Creek during periods of precipitation.

The dump just below the Weil Portal of the Balaklala Mine is typical of the third type of dump, dominated by waste rock with minor amounts of pyrite. Water flowing from the mine infiltrates the dump and reappears near the bottom of the dump. On the day sampled, the mine effluent at the top of the dump had a pH of 1.8 and at the bottom of the dump a pH of 2.2. Major processes which take place in the dump include dilution of the effluent with other water, evaporation of the effluent, and cementation of the dump with iron hydroxides and oxides. Residence time of the effluent in the dumps is short, owing to high porosity and permeability.

BIOLOGICAL INDICATORS

To determine the effects of acid and dissolved-metal effluent on the biota of West Squaw and Little Backbone Creeks, a study of benthic invertebrates was made during the autumn of 1975. The objectives of this study were to determine the species composition of organisms in the streams and their relative abundance, and to evaluate the usefulness of benthic invertebrates as indicator organisms to monitor subsequent changes in water quality. Sampling sites for West Squaw Creek are shown in figure 2 and for Little Backbone Creek in figure 3. Organisms were collected using a 144-in^2 Surber sampler (Slack and others, 1973). One to four samples were taken at each sampling site depending on conditions at the site. An effort was made to take all samples from riffle areas. Samples were preserved in the field in formalin, then identified in the laboratory and preserved in 70-percent ethanol. Species lists of organisms are given in tables 6 and 7.

Patrick (1949) defined a "healthy stream" as an undamaged stream that supports a diverse and balanced flora and fauna, with all trophic levels proportionally represented and with no obvious population imbalances. Cummins (1973) listed the trophic levels of benthic organisms according to their feeding mechanisms: Shredders, collectors, scrapers, and predators. Specific organisms may also be indicative of specific water-quality conditions. According to Oliver (1971), the normal range of water pH for most species of chironomids is from 6 to 8; however, Harper and Campbell (1967) reported that larval stages of the chironomid, *Chironomus plumosus*, have been found in water having a pH of 2.3, but that no pupae developed to adults. The insect fauna most severely affected by acid water include Odonata, Ephemeroptera, and Plecoptera. Insect communities also may develop acid-resistant species (Parsons, 1968).



	Sampling site						
	6	7	8	9	10	11	12
Diversity	2.751	2.108	2.577	0.975	0.102	0.784	0.043
Number of species	25	6	18	6	4	2	3
Number of individuals per square meter	2096.3	123.8	1044.1	236.8	3326.2	322.9	9068.9
pH	6.5	3.6	6.5	4.00	2.4	2.75	2.7

FIGURE 3.-- Benthic sampling sites, and analyses of sampling on Little Backbone Creek.

TABLE 6.--*Benthic sample analyses, West Squaw Creek drainage*

[L = larva. Site locations are shown in figure 2]

Sampling site	1	2	3	4	5
Area sampled, in square meters	0.36	0.18	0.18	0.09	0.09
			Number of organisms		
Tricoptera					
Psychomiidae					
Polycentropus sp. (L)	1	-	-	-	-
Diptera					
Ceratopogonidae					
Forcipomyia sp. (L)	4	-	50	4	1
Bezzia sp. (L)	7	-	-	-	-
Chironomidae					
Tribe Tanytarsini					
Micropsectra sp. (L)	2	-	-	-	-
Subfamily Orthocladiinae					
Orthocladius sp. (L)	-	-	20	-	-
Eukiefferiella sp. (L)	2	-	-	-	-
Thienemanniella sp. (L)	30	2	-	3	1
Acari (aquatic)	-	1	-	-	-

The results of the biological sampling may be quantified by use of the Shannon-Wiener diversity index (Krebs, 1972):

$$H = - \sum_{i=1}^{s} (P_i) (\log^2 P_i) \qquad (6)$$

where H = information content of the sample = diversity,
s = number of species, and
P_i = proportion of total sample belonging to the ith species. In this diversity index a population made up of only one species would have a diversity of zero, whereas a population having more than one species has a diversity greater than zero. As a general rule, populations of organisms in water of good chemical quality have a diversity approaching or exceeding two, whereas organisms in badly polluted water generally have a diversity of one or less. Diversities of samples taken in West Squaw and Little Backbone Creeks are shown in figures 2 and 3, respectively.

TABLE 7.--*Benthic sample analyses, Little Backbone Creek drainage*

[L, indicates larva; N, indicates nymph; P, indicates pupa; and A, indicates adult]

Sampling site (shown in fig. 3)	6	7	8	9	10	11	12
Area sampled, in square meters	0.36	0.18	0.36	0.36	0.18	0.18	0.18
Ephemeroptera				Number of organisms			
Baetidae							
Baetis sp. (N)	141	3	74	3	–	–	–
Heptageniidae							
Iron sp. (N)	29	1	2	–	–	–	–
Ironodes sp. (N)	4	–	2	–	–	–	–
Heptagenia sp. (N)	1	–	–	–	–	–	–
Leptophebiidae							
Paraleptophlebia sp. (N)	1	–	–	–	–	–	–
Odonata							
Libellulidae							
Paltothemis lineatus (N)	–	–	1	–	–	–	–
Ceonagrionidae (N)	1	–	1	–	–	–	–
Plecoptera							
Chloroperlidae							
Alloperla sp. (N)	8	–	4	–	–	–	–
Neuroptera							
Corydalidae							
Protochauliodes sp. (L)	2	–	–	–	–	–	–
Tricoptera							
Rhyacophilidae							
Rhycophila nr. *vaccua* (L)	1	–	–	–	–	–	–
Philopotamidae							
Wormaldia sp. (L)	–	–	1	–	–	–	–
Psychomiidae							
Polycentropus sp. (L)	2	–	8	3	–	–	–
Hydropsychidae							
Hydropsyche sp. (L)	3	–	–	–	–	–	–
Parapsyche sp. (L)	1	–	–	–	–	–	–
Coleoptera							
Dytiscidae							
Oeronectes griseotriatus (A)	–	–	–	–	–	–	3
Limnebiidae (Hydraenidae)							
Hydraena vandykei (A)	4	–	–	–	–	–	–
Diptera							
Tipulidae							
Hexatoma sp. (L)	–	–	1	–	–	–	–
Dicranota sp. (L)	3	–	–	–	–	–	–
Psychodidae							
Maruina lanceolata (L)	53	1	6	–	1	–	–
Ceratopogonidae							
Forcipomyia sp. (L)	–	–	–	–	–	–	–
Bezzia sp. (L)	4	–	–	–	5	–	–
Chironomidae							
Tribe Pentaneurini (L)	46	–	25	1	–	–	–
Tribe Chironominae (L)	1	–	7	–	–	–	–
Tribe Tanytarsini							
Micropsectra sp.	12	–	8	–	–	–	–
Subfamily Orthocladiinae							
Orthocladius sp. (L)	7	–	20	–	611	14	–
Eukiefferiella sp. (L)	4	11	2	5	1	–	4
Cricotopus sp. (L)	104	–	55	–	–	–	–
Thienemanniella sp. (L)	21	3	1	74	–	46	1,678
Simuliidae (L)	321	4	170	2	–	–	–
Simulium virgatum (P)	4	–	–	–	–	–	–
Nematada							
Nemata sp. (L)	1	–	–	–	–	–	–

West Squaw Creek

Five sites were chosen for benthic sampling on West Squaw Creek and its tributaries (fig. 2). The first site is on the South Fork of West Squaw Creek just upstream from debris associated with the Shasta King Mine. The second site is just above the point where the effluent from the Weil Portal enters the creek. Site 3 is on the Weil Portal effluent. Site 4 is on the South Fork of West Squaw Creek below its confluence with the Weil effluent. Site 5 is on the creek just before it enters Shasta Lake.

Site 1 is already acid (pH=3.6) from upstream input of drainage from the main workings of the Balaklala Mine. Organisms at this site include three species of Chironomidae and one of Psychomiidae, all of which are filter feeders. The only other trophic level present is that of predators, composed of midges of the genera *Forcipomyia* sp. and *Bezzia* sp., and aquatic mites, Acari. Water is of poor biological quality if organisms fill only a limited number of trophic levels (Patrick, 1949). Water samples from sites 2, 3, 4, and 5 were also of poor biological quality, yielding only two or three species and generally low densities. This is attributed to the low pH and large concentration of dissolved metals. Diversities also were generally low.

Little Backbone Creek

Sampling along Little Backbone Creek was done at seven sites (fig. 3). Two sites, numbers 6 and 8, are on the North Fork of Little Backbone Creek. Sites 7, 9, 11, and 12 are on Little Backbone Creek proper, and site 10 is on a small tributary that drains the Mammoth Mine area. Species composition and enumeration are shown in table 7 for all sampling sites in the Little Backbone Creek drainage.

Samples from sites 6 and 8 were used as standards for comparison with samples from the other sites, because the water in the North Fork was of good chemical and biological quality (fig. 3). Samples from site 6 had 25 species of organisms, and samples from site 8 had 18 species. Diversities were 2.751 and 2.577, respectively.

Sites 6 and 8 contained insects which represent all trophic levels. Shredders included the choronomid *Cricotopus* sp., a chewer and miner living on vascular plants; collectors, which feed by gathering material by filtering suspended material in water, included chironomids (*Thienemanniella* sp., *Orthocladius* sp., and *Eukiefferiella* sp.), Simuliidae, and Tricoptera (*Wormaldia* sp., *Polycentropus* sp., and *Hydropsyche* sp.). Scrubbers included Ephemeroptera (*Baetis* sp., *Iron* sp., and *Ironodes* sp.), and predators included Neuroptera (*Protochauliodes* sp.), Odonata (*Paltothemis lineatus*), Plecoptera (*Alloperla* sp.), and a chironomid (*Pentaneurini*).

The creek water at site 7 (fig. 3) has already suffered some degradation as indicated by a pH of 3.6 and a diversity of 2.108. Only six species of organisms were found at this site. Of these, only four Ephemeroptera were present as compared to an average of 127 at sites 6 and 8.

Water at site 9, downstream from the confluence of the main stream and the North Fork of Little Backbone Creek, is heavily influenced by the water flowing past site 7 and polluting the flow from the North Fork. Site 9 water has a pH of 4.0, a diversity of 0.975, and only six species of organisms.

Water from site 10, on the acid effluent from the Mammoth Mine, has the lowest pH, 2.4, of any site on Little Backbone Creek (fig. 3). It has a low diversity, 0.101, and only four species of organisms are present. Of these species, 98.9 percent are the chironomid *Orthocladius* sp., which has been noted as being acid tolerant. The highly acid water entering Little Backbone Creek from the Mammoth Mine resulted in decreased diversities for samples from stations 11 and 12, as compared with diversities for samples from stations 6, 8, and 9. The most notable change was the small diversity of 0.043 at station 12. This probably is due to the vast numbers of the chironomid *Thienemanniella* sp., which constituted 99.5 percent of the organisms and accounted for the largest density of organisms present at any site on the creek. The large numbers of *Thienemanniella* sp. probably were owing to the lack of competition and predation as a result of water-quality conditions in which other organisms could not survive. In addition, site 12 may have been more nearly a pool than a riffle, which may account for some of the increase in density.

LABORATORY STUDIES

Several laboratory experiments were made to investigate acid generation and metal mobilization in pyritic dump material. These experiments included determinations of the relationship between water contact time with dump material and acid generation, metal release, and acid-generation capacity. For purposes of these experiments, pyritic mine dump material was collected from the Keystone and Balaklala Mine dumps (fig. 1). This material was sieved to remove material larger than 0.079 inch, using a nylon sieve. One hundred grams of pyritic material was then packed into chromatographic columns, columns were saturated with deionized water, and water was then allowed to flow down through the pyritic material at a constant rate.

As deionized oxygenated water was passed directly through columns of pyritic material, it was noted that an initial flux of highly acid water was followed by decreases in the amount of acid generated as more water was allowed to flow through the system (fig. 4). This indicates that there is a highly acidic material, possibly ferric iron, on the surfaces of the weathered pyrite found in the dumps. As a result, runoff from the first major storm of the year could produce significant quantities of acid. Figure 4 also shows that after the initial flux of acid, lower level acid generation may continue.

Acid generation with deoxygenated water was found to be almost identical to that with the oxygenated water, indicating the presence of ferric iron which can form acid in the presence of water but without requiring oxygen, according to equation 3:

$$Fe^{+3} + 3H_2O \rightleftharpoons Fe(OH)_3 + 3H^+ \qquad (3)$$

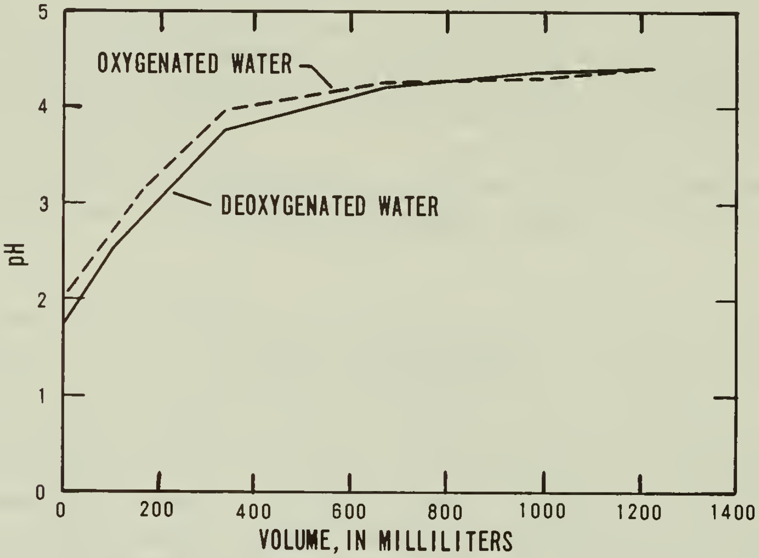


FIGURE 4.--pH of oxygenated water and deoxygenated water flowing through columns of Balaklala Mine dump material.

Deionized water was also recirculated through 100 grams of pyritic material to determine the contact time necessary for water to come to equilibrium with the pyritic material. For an initial 100 milliliters of water, this took about 20 minutes of contact time and resulted in an effluent with a pH of 1.80, an acidity of 12,000 mg/L as $CaCO_3$, and a specific conductance of 15,400 μmho/cm. Dissolved-metal concentrations included: Iron, 1,300,000 μg/L; manganese, 2,000 μg/L; copper, 15,000 μg/L; lead, 2,600 μg/L; and zinc, 21,000 μg/L. When a second 100 milliliters was recirculated for 20 minutes after the initial effluent was removed, much lower values were found. These included a pH of 2.5, an acidity of 2,380 mg/L as $CaCO_3$, and a specific conductance of 4,050 μmho/cm. Metal concentrations for this second sample were: Iron, 130,000 μg/L; manganese, 160 μg/L; copper, 1,100 μg/L; lead, 600 μg/L; and zinc, 1,700 μg/L. These results indicate that, in addition to large acid generation capacity, a large pulse of dissolved metals may be expected in the first runoff from the dump following a dry period.

CONTROL OF ACID MINE EFFLUENT

Many methods for reduction or control of acid effluent from underground mines are reported in the literature. Most treatment methods can be lumped into three major groups: (1) Sealing, (2) treatment, generally neutralization, of mine effluent, and (3) infiltration control. Although sealing mine portals has the potential advantage of eliminating the acid effluent, it is often difficult to accomplish, of uncertain reliability, and generally expensive. Treatment of effluent by neutralization is effective but does not remove the source so that treatment must be continued indefinitely. Where applicable, infiltration control is generally the simplest and one of the less expensive methods of reducing acid effluent; however, complete infiltration control can seldom be accomplished.

Certain ground rules were established in discussions with the staff of the Central Valley Regional Board at various times during the study that substantially influenced the selection of a demonstration site and methods of water-quality control.

The following criteria were used to evaluate site selections for water-quality control:

1. Reasonable vehicular access was mandatory. Because of this, the East Shasta Mining District, accessible only by boat or helicopter, was omitted from consideration. A number of sites in the West Shasta District were ruled out because some roads have not been maintained for 30 years or longer.

2. So far as practicable, sites amenable to simple, low-cost methods were preferred over those where more elaborate or high-cost methods were required.

3. Active water-quality control systems, those systems needing maintenance, were avoided in preference to passive systems. Chemical treatment, generally accepted as state-of-the-art for eliminating acid mine effluent, requires constant maintenance and was therefore considered only as a last resort.

Sealing Mines

There are two mine-sealing techniques that could be used in the study area, hydraulic sealing and air sealing. Hydraulic sealing is accomplished by placing one or more bulkheads in mine tunnels to prevent the escape of water, thus eventually flooding the mine workings and preventing oxygen from reaching the pyrite. This method of sealing requires that the mine and surrounding area be geologically sound and able to withstand the hydraulic pressure caused by the water that backs up in the mine. Drill holes would have to be plugged. If the area is badly fractured, hydraulic sealing is impractical. Air seals allow water to flow out of the mine but prevent the entrance of air into the mine by means of a wall with a water trap at its bottom. Over a period of time, free oxygen in the mine is depleted or at least reduced by oxidation, thereby eliminating oxygen as a source for acid generation. Air seals have not been effective in reducing acid production in coal mines because of the numerous air passages such as boreholes, joints, fractures, and subsidence cracks that allow air to enter the mine. Differences in barometric pressure outside the mine cause air to flow into and out of the system. Hardrock mines, however, with thick and sound overburden and a minimum amount of openings to the surface, may offer an opportunity to attempt air sealing. Both sealing methods were discussed in detail by the U.S. Environmental Protection Agency (1973, 1975a, 1975b).

There are no documented cases of successful sealing of hardrock mines in the United States, Canada, or Europe, although there is a reported case in Japan (R. D. Hill, oral commun., 1976). All sealing efforts in the United States have been directed toward control of coal-mine drainage.

Prerequisite to sealing any of these mines is the ability to obtain access to the mines with heavy equipment, such as drills, air compressors, and concrete mixers. Therefore, only mines with access by roads over which this equipment could be carried are suggested in this report. Mines are generally drained before seals are placed. In addition, it is preferable to work within the mine tunnel, when possible, rather than injecting cement and grout material through drill holes. Construction inside the mine may require cleaning out and shoring part of the tunnel in order to meet mine-safety standards.

Treatment of Effluent

Of the many treatment methods that have been developed, neutralization of acid water which results in coprecipitation of ferric hydroxide and dissolved metals merits serious consideration for use on effluent in the Shasta Mining District. Neutralization could be accomplished by mixing a number of basic materials with the acid water, including limestone, lime, magnesium oxide, sodium hydroxide, and sodium carbonate (Hill, 1968). Of these possible neutralizing agents, lime is probably the best choice for the Shasta area because it is readily available as a byproduct from a portland cement plant located near the mining districts. In addition, lime is fast acting, and produces a minimum volume of precipitate. Limestone also is readily available in the area, but unless finely crushed it may be unsatisfactory because of the length of time necessary for neutralization. Crushing would, of course, greatly increase its cost. The steep slopes of the Shasta area offer the possibility of using hydraulic heads to operate line feeders that mix and aerate the treated water, thus reducing operating and construction costs. Sites for settling ponds to remove the precipitated material are limited.

Runoff and Infiltration Control

Infiltration control can be used to effectively reduce the amount of water entering mines. Infiltration control could be accomplished by diversion of surface water to prevent it from flowing into the mines through caved stopes and other openings. In addition, infiltration control should include steps to channel water away from dumps of mine waste. Grading of dumps followed by covering with a layer of impermeable material such as clay would reduce infiltration and retard erosion of the dumps.

CONCLUSIONS AND RECOMMENDATIONS

A number of tributaries entering the Sacramento River and Shasta Lake contain significant concentrations of acid and dissolved metals, predominantly iron, copper, and zinc. These tributaries include Spring Creek, draining the Iron Mountain mining complex; Flat Creek, draining a processed ore dump near Minnesota; West Squaw Creek, draining the Keystone, Balaklala, and Shasta King mines; and Little Backbone Creek, which drains the Mammoth and Golinsky mines in the West Shasta Mining District. In the East Shasta Mining District, streams carrying the highest concentrations of acid and metals are Horse Creek and Town Creek, both of which drain the Bully Hill mining complex.

Suggested Abatement Procedures

Initially, abatement procedures can be tried in selected streams and mines in the West Shasta District. If effective procedures are developed, they might, in varying degrees, be adaptable to other streams and mines in both the West and East Shasta Mining Districts.

Flat Creek has the least complex pollution problem of any of the creeks studied. All apparent effluent is generated by water seeping over and through a processed-ore dump. The ponding of water on the dump by a small dam greatly increases contact time between water and dump material and increases acid and dissolved-metal concentrations in the water. Mine effluent entering the stream was not seen at any point along its course. The quantity and acidity of the dump effluent probably could be reduced if runoff in the area near the dump were channeled or diked away from the dump and the dump were graded to eliminate the pond and induce prompt discharge of water from the surface. Removing the dam and sealing the dump with impermeable material would promote runoff while reducing erosion and infiltration. This site is accessible and offers a good location to evaluate runoff- and infiltration-control procedures on a mine dump because the dump is the sole known source of pollution. The Flat Creek site is therefore suggested as the site for a pilot study to evaluate the effectiveness of infiltration and runoff control in reducing acid generation in mine dumps.

The Keystone Mine presents a more complex problem than the dump on Flat Creek because most of the effluent originates within the mine. In addition, a small dump in front of the main adit contains large quantities of pyritic material. The mine has three adits, however, which provide an opportunity to demonstrate air seals or hydraulic seals, or both. The demonstration would be unique because neither method of sealing has commonly been used in hardrock mines (R. D. Hill, written commun., June 17, 1975).

Solid-wall air seals could be positioned so as to close the two upper adits to the atmosphere, whereas a water seal, allowing water to flow out of the mine but excluding oxygen, could be placed on the main adit. Laboratory studies indicate that acid may be generated in pyritic material in oxygen-free water. The oxidizing agent in that case is thought to be ferric iron (see equation 4). In the mines, however, the ferric iron is a finite element which will, after a period of time, be exhausted. Air seals therefore may take a long period to become effective. If air seals are not successful, bulkhead seals could be tried; however, hydraulic heads as great as 160 ft would make bulkhead sealing difficult and probably expensive. The presence of many exploratory drill holes and fractures make containment problematic. Seepage through the dump outside the main adit could be significantly reduced by channeling surface runoff and mine effluent away, grading to promote runoff and minimize erosion, and sealing with clay or other poorly permeable material.

Because of the character of the mine itself, the probable high cost of installation of seals and the uncertainty about the effectiveness of seals, the Keystone Mine is a poor site for a demonstration project.

The Balaklala Mine complex, because of its size, poses difficult problems in pollution abatement. The size of the workings and the number of adits preclude a program of sealing at reasonable cost. Procedures that could be immediately applied to reduce the acid and metal output of the Balaklala Mine complex include channeling of surface water and mine effluent away from dumps and collapsed mine areas, possibly grading and sealing the dumps to minimize seepage through tailings and to prevent erosion, and neutralization of effluent from the dumps.

At the surface, the upper part of the Balaklala mine consists of a main portal and one adit, both of which discharge water onto a large waste dump containing a large pond of acid, metal-bearing effluent. This effluent drains into West Squaw Creek. Upgradient from the main portal are two caved stopes which appear as large holes at the surface, 8 to 10 ft in diameter and 10 to 15 ft in depth. Water from a springfed stream flows into one of the holes, as does water flowing downslope from the Keystone Mine dump. A preliminary step to any attempt at water-quality control in the Balaklala Mine should be to collect the water flowing into the collapsed stope and divert it downstream to a point below the mine dump at the main workings. The holes in the roof of the stope could be plugged to insure that water will no longer flow into the mine. The holes also are a hazard to public safety, as the area is used by recreationists (motorcyclists and others).

Once the flow of water into the Balaklala Mine is stopped, outflow should be observed for a sufficient period of time to determine whether it has been significantly reduced or stopped. If outflow is stopped or reduced to insignificance, the problem of acid water would be reduced to elimination of other sources of water that reach the mine dumps. If mine effluent is not significantly reduced, other measures might be required.

The Weil Portal of the Balaklala Mine, downslope and east of the main portal area, is the best site in the West Shasta Mining District for a demonstration program in control of acid mine effluent. The site presents several aspects of acid mine drainage problems that are common to other mines in the West Shasta Mining District. Effluent from the portal is highly acid (pH 2.0 on September 17, 1976) and there is a flow of much less acid water adjacent to the portal that mixes with the effluent and flows through a tailings pile where exposure to the pyritic material in the pile increases acid generation. Downgradient from the tailings pile, the water flows in a narrow, steep-sided channel until it reaches the South Fork of West Squaw Creek.

There are several possible approaches to a water-quality control experiment at the Weil Portal site. The one suggested is a three-step system designed to (1) prevent generation of acid in part of the water by diverting it around the mine dump below the portal, (2) control infiltration of water through mine dumps by grading the dumps and attempting to cover the graded dumps with a layer of material which would inhibit the infiltration of water, and (3) chemically treating the acid water from the mine and dump by causing it to flow through calcium carbonate. Following each step the effect of the treatment would be evaluated to determine if it is necessary to move to the next step.

The scheme presented here is not applicable in all respects to other sites in the area, but it represents an opportunity to demonstrate results of a quality-control experiment in one element of the West Squaw Creek drainage system. A similar plan could be applied to topographically higher portals of the Balaklala Mine, but because that locality involves a more complex flow system, larger quantities of water, and longer distances for diversion, the cost would be higher.

The proposed demonstration project at the Weil Portal is schematically diagramed in figure 5. The first step is construction of collection structures near the portal to prevent runoff from mixing with the acid mine effluent. These structures could be built of wood and lined with plastic or could be made more permanent by use of concrete. Water diverted by the structures would flow to a diversion ditch, preferably lined with waterproof material. An open ditch is recommended over a pipeline because the ditch can intercept peripheral runoff. The water would be diverted down the steep side of the canyon to a point downstream from the mine dump. This ditch would prevent water of relatively good quality from flowing through the highly pyritic mine dump and becoming acidified. The diverted water would return to the original channel at a point downstream where it would dilute any water that continued to flow through the mine dump.

If, after evaluation, the water quality downstream from the dump is unsatisfactory, a second step in quality control could be undertaken by grading the surface of the mine dump to reduce erosion, minimize infiltration, and induce prompt movement of water from the dump. Surfacing the dump with impervious material such as clay or asphalt would inhibit infiltration. Soil-type materials would not be likely to stay on the steep slopes as they are highly erodible. It is not likely that any vegetation could be induced to grow on the dump, owing to the acidity of the material. A vegetative cover on the dump would be aesthetically pleasing but counterproductive in that it would increase infiltration. The effectiveness of this step is highly speculative and awaits implementation before a comprehensive evaluation could be made.

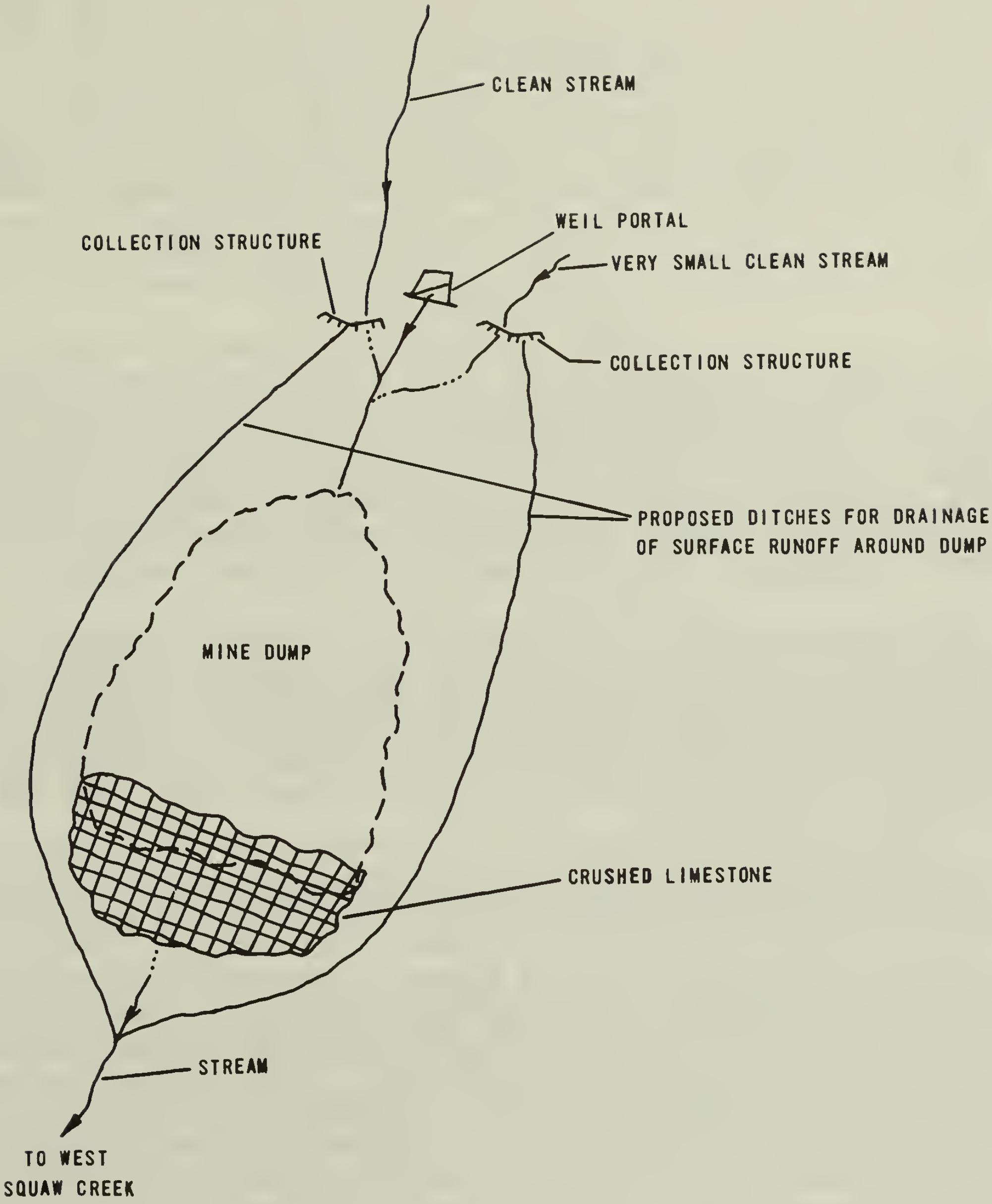


FIGURE 5.--Schematic diagram of proposed acid mine-drainage abatement procedures for the Weil Portal area.

If evaluation of the preceding measures indicates that they are inadequate, then the third and final step suggested for water-quality control at this site is treatment of the acid effluent as it leaves the mine dump. At the downstream end of the mine dump, the stream channel leading from the dump could be packed with pebble-sized crushed calcium carbonate 10 to 15 ft thick. Limestone outcrops in the vicinity could be used as a source for this material. The limestone could be trucked to the site and poured into place from the top of the tailings pile using a portable chute. A retaining structure would probably have to be built to hold the crushed limestone in position and to insure that the effluent from the tailings pile gets maximum exposure to the limestone. The water flowing out of the limestone would then be diluted by mixing with the water that was routed around the tailings pile.

The scheme of using crushed limestone for treatment probably is suitable only for a short-term demonstration, as the limestone can be expected to become coated with precipitates and thereby prevented from reacting with the acid water. In the long run, treatment will require appropriate mechanical or hydraulic structures to insure that, if limestone is used, it will be abraded so the water will have ample contact with fresh surfaces, or if slurry processes are used, such as injection of a lime slurry, the acid water is well mixed with appropriate concentrations of the treatment solution.

The portals and dump of the upper part of the Balaklala Mine also are suitable for a scheme similar to the one suggested for the Weil Portal; that is, water diverted around the mine dump, the surface of the dump graded and sealed with an impermeable material, and, if necessary, the water treated to neutralize acid at a point downstream from the dump. The topography is rough and distances involved are greater than at the Weil Portal, but the elements of the problem are similar.

At either site, each step in control or reduction of acid mine drainage should be monitored to determine whether subsequent steps must be undertaken.

The Shasta King Mine does not appear to contribute significant quantities of acid water to the West Squaw Creek system; however, the mine consists of many adits that face on the creek, and material from those adits was dumped adjacent to or into the creek during the many years of mine operation. The accumulated pyritic waste material in the creekbed represents a monumental problem in water-quality control. If all other measures fail to bring the water in the West Squaw Creek area to an acceptable level of quality, the only remaining alternative will require chemical treatment of the water downstream from the Shasta King Mine.

The Mammoth Mine does not readily lend itself to a demonstration project. The mine is large, with at least 15 adits. Dumps are on steep slopes, making any attempts to grade or seal them very difficult. The only apparent abatement method that could be attempted with reasonable effort would be a neutralization plant at the 470-ft level of the mine. This is the location of the largest acid discharge from the mine.

The Spring Creek drainage should be evaluated because it is the major source of acid and dissolved metals. This system may well lend itself to the development of a neutralization plant. A plant could be placed on Spring Creek or on Slickrock Creek just before the creek enters Spring Creek. Access to Slickrock Creek would require some road building, as would access to Spring Creek above the Spring Creek Debris Dam. A site below the dam is readily accessible, although it would be difficult to collect the floc and prevent it from entering Keswick Reservoir. This is a site where recovery of copper and other metals to offset some of the costs of treatment could be evaluated.

Water-Monitoring Program

To determine the effectiveness of any program designed to control metal-contaminated, acid-bearing effluent, a comprehensive water-monitoring program must be undertaken. Such a program should have two phases. In the first phase, background information should be collected on water chemistry, loads of pollutants, and biological quality of water in the reaches downstream from the area being treated. This phase was basically completed in the study presented in this report.

The second phase of the water-quality monitoring program should begin after acid-drainage abatement methods have been started. Data from the second phase, when compared to the background measurements, should provide a comprehensive picture of the effects of selected treatment methods on water quality in streams.

Chemical properties and constituents monitored should include pH, specific conductance, dissolved solids, calcium, iron, manganese, sulfate, copper and zinc. Identification of periphyton and determinations of their relative abundance should be made. Benthic invertebrates in the streams should be sampled as indicators of changes in water chemistry (Herricks and Cairns, 1973). Changes in species composition of the population, especially the less tolerant species of Odonata, Ephemeroptera, and Plecoptera, generally reflect changes in water-quality conditions. Diversity of the benthic invertebrates should also be computed. Past studies generally have shown a rapid repopulation of streams by drift organisms following abatement of acid discharges (Herricks and Cairns, 1973).

REFERENCES CITED

Albers, J. P., and Robertson, J. F., 1961, Geology and ore deposits of East Shasta Copper-Zinc District, Shasta County, California: U.S. Geol. Survey Prof. Paper 338, 107 p.

Cummins, K. W., 1973, Trophic relationships of aquatic insects: Ann. Rev. Entomology., v. 18, p. 183-206.

Hansen, R. J., and Weidlein, W. D., 1974, Investigation of mine drainage related fish kills in the Little Squaw Creek Arm of Shasta Lake, Shasta County, California: Calif. Dept. Fish Game Adm. Rept. 74-2, 21 p.

Harper, G. L., and Campbell, R. S., 1967, The distribution of *Tendipes pulmdsus* (Linne) in mineral acid water: Limnology and Oceanography, v. 12, no. 2, p. 260-263.

Herricks, E. E., and Cairns, J., Jr., 1973, Rehabilitation of streams receiving acid mine drainage: Virginia Water Resources Research Center, Bull. 66, 284 p.

Hill, R. D., 1968, Mine drainage treatment-state of the art and research needs: [U.S.] Federal Water Pollution Control Adm., Mine Drainage Control Activities, Cincinnati, BCR68-150, 101 p.

Kinkel, A. R., Jr., Hall, W. E., and Albers, J. P., 1956, Geology of base-metal deposits of West Shasta Copper-Zinc District, Shasta County, California: U.S. Geol. Survey Prof. Paper 285, 156 p.

Krebs, C. J., 1972, Ecology; the experimental analysis of distribution and abundance: New York, Harper and Row, 694 p.

Nordstrom, D. K., Jenne, E. J., and Averett, R. C., 1977, Heavy metal discharges into Shasta Lake and Keswick Reservoirs on the upper Sacramento River, California--A reconnaissance during low flow: Menlo Park, Calif., U.S. Geol. Survey Water-Resources Inv. 76-49, 25 p.

Nordstrom, D. K., 1977, Hydrogeochemical and microbiological factors affecting the heavy metal chemistry of an acid mine drainage system: Palo Alto, Stanford Univ., unpub. Ph. D. thesis, 210 p.

Oliver, D. R., 1971, Life history of the chironomidae: Ann. Rev. Entomology, v. 16, p. 211-230.

Parsons, J. O., 1968, The effect of acid strip-mine effluents on ecology of a stream: Archiv Hydrobiologie Beihefte--Ergebnisse Limnologie, v. 65, no. 1, p. 25-50.

Patrick, Ruth, 1949, A proposed biological measure of stream conditions based on a survey of the Conestoga Basin, Lancaster County, Pennsylvania: Acad. Nat. Sci. Philadelphia, Proc., v. 101, p. 277-341.

Potter, R. W., II, 1976, The weathering of sulfide ores in Shasta County, California, and its relationship to pollution associated with acid mine drainage: U.S. Geol. Survey Open-File Report 76-395, 18 p.

Slack, K. V., Averett, R. C., Greeson, P. E., and Lipscomb, R. G., 1973, Methods for the collection and analysis of aquatic biological and microbiological samples: U.S. Geol. Survey Techniques Water-Resources Inv., book 5, chap. A4, 164 p.

Stumm, Werner, and Morgan, J. J., 1970, Aquatic chemistry; an introduction emphasizing chemical equilibria in natural waters: New York, Wiley-Interscience, p. 525-544.

U.S. Environmental Protection Agency, 1973, Processes, procedures, and methods to control pollution from mining activities: EPA-430/9-73-011, 390 p.

______1975a, Inactive and abandoned underground mining; water pollution prevention and control: EPA-440/9-75-007, 338 p.

______1975b, Criteria for developing pollution abatement programs for inactive and abandoned mine sites: EPA-440/9-75-008, 543 p.